Shape Optimisation of Axisymmetric Scramjets

Hideaki Ogawa

11th International Workshop on Shock Tube Technology
Australian Hypersonics Workshop 2011
University of Queensland, Brisbane

23rd March 2011

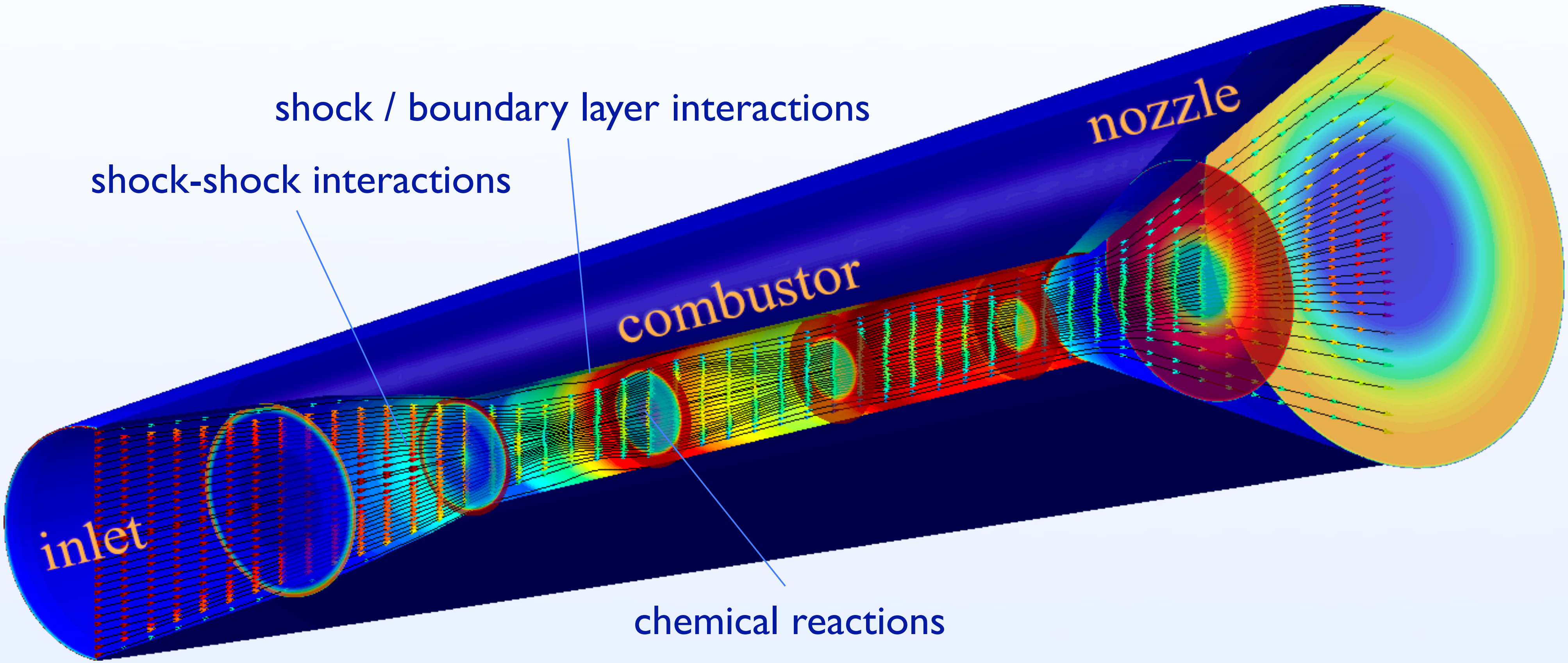
Overview

- Introduction
  - Axisymmetric Scramjet Engines
  - Approach (Optimisation & CFD)
- Results
  - Inlet Design Optimisation
  - Nozzle Design Optimisation
  - Full Flow-Path Optimisation
- Conclusions

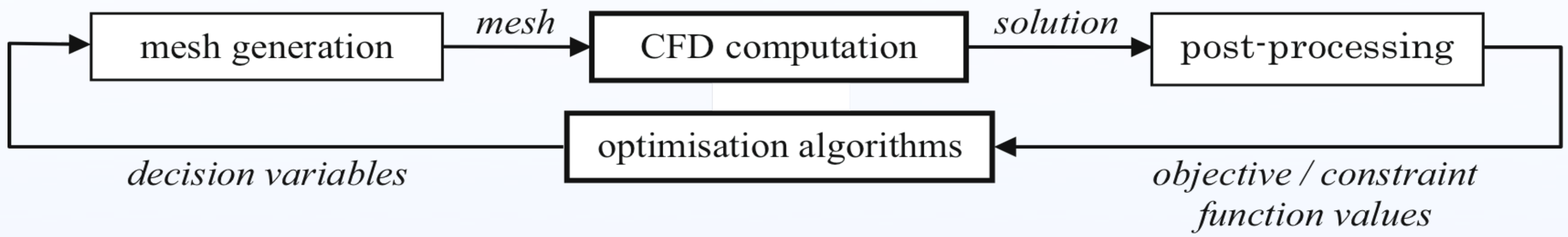
Shape Optimisation of Axisymmetric Scramjets

Introduction

Axisymmetric Scramjet Flowfield



Design Optimisation Methodology



- Design optimisation capability developed at UNSW@ADFA
  - **Evolutionary algorithms**
    (elitist non-dominated sorting genetic algorithm NSGA-II)
  - Population with 32 - 64 individuals over 30 - 50 generations
  - Probabilities of recombination operators:
    Simulated binary crossover = 100%, Polynomial mutation = 10%
  - **Surrogate prediction** (using 90% of solutions in archive)
    response surface models, kriging approximation, radial basis functions

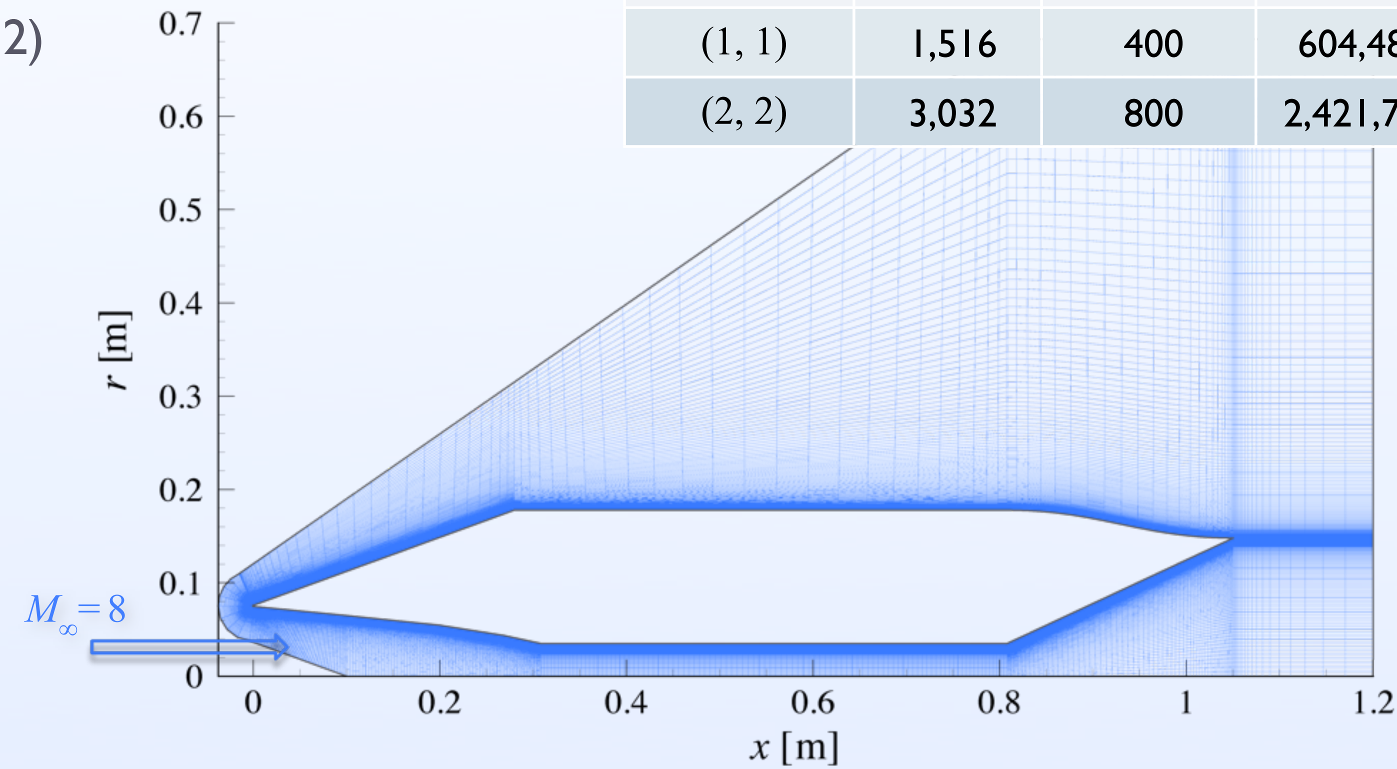
Computational Fluid Dynamics

- Solver
  - CFD++ (Metacomp, Inc.)
  - Implicit algorithm + multigrid acceleration
  - 2nd order spatial accuracy
  - Convergence order = 10^{-3} - 10^{-5}
- Assumptions
  - Boundary layer: fully turbulent (2-equation SST k-ω RANS model)
  - Gas: Equilibrium air (inlet) / Evans & Schexnayder's model 12 species and 25 elementary reactions)
  - Surface: isothermal cold wall (300K)

Computational Mesh

- Mesh resolutions
  - Pointwise grid generator
  - Fully structured mesh
  - Min. cell width = 10^{-5} m (y^+=0.32)

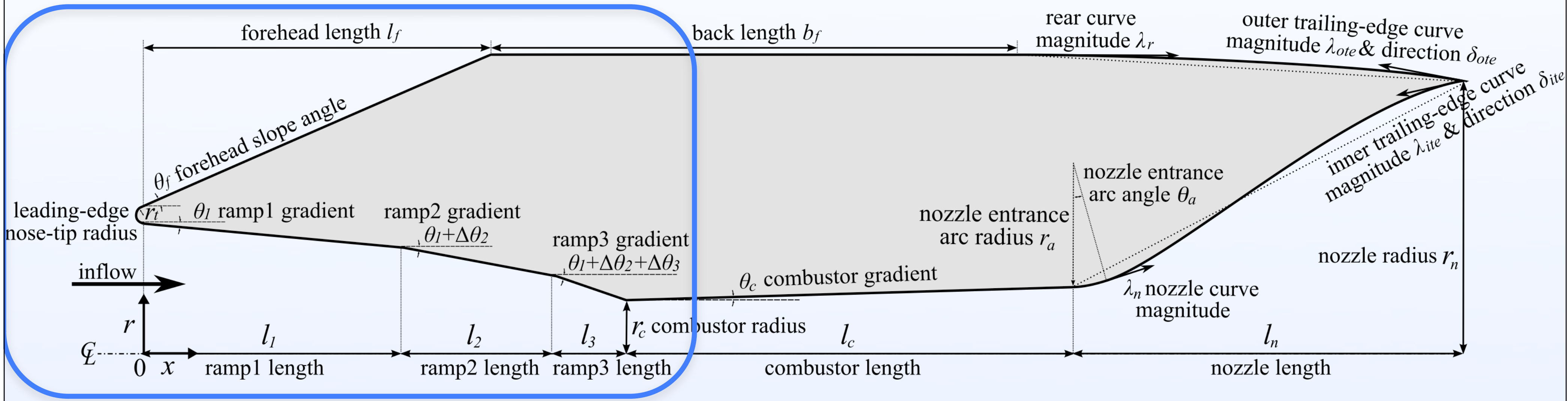
(m_x, m_y)	wall	vertical	cells
(1/2, 1/2)	758	100	74,943
(1/4, 1)	379	200	75,222
(1/2, 1)	758	200	150,643
(1, 1)	1,516	400	604,485
(2, 2)	3,032	800	2,421,769



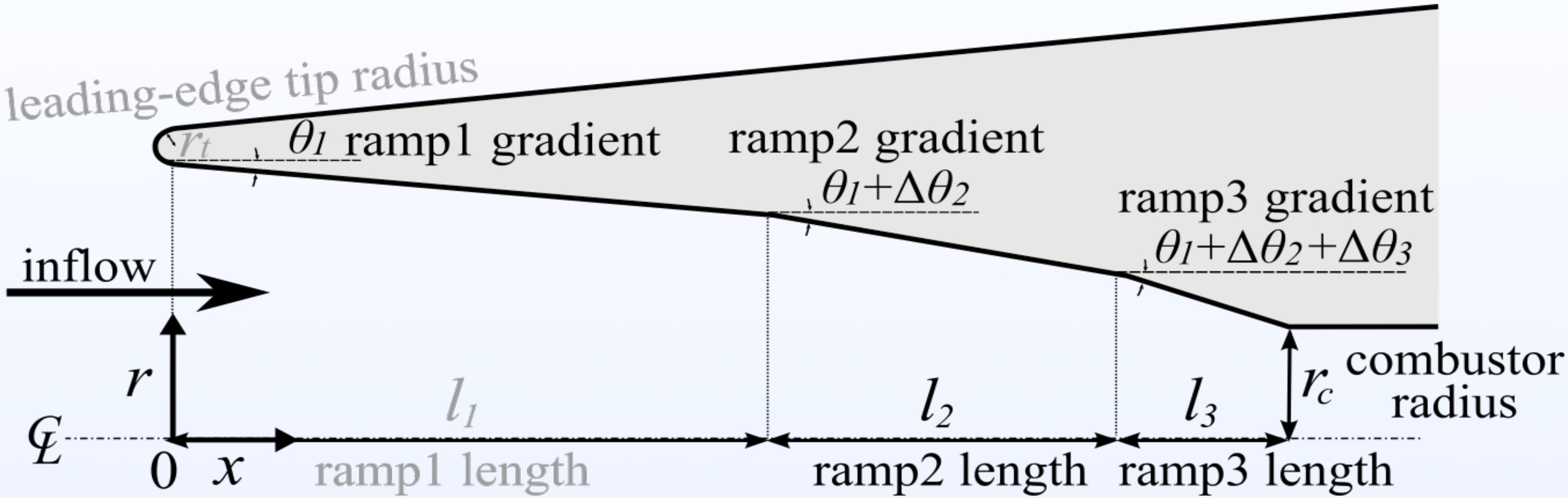
Shape Optimisation of Axisymmetric Scramjets

Results

Inlet Design Optimisation



Design Parameters



8 parameters: l_1, l_2, l_3, θ_1, $\Delta\theta_2$, $\Delta\theta_3$, r_c, r_t

inlet area and r_t fixed

6 decision variables: l_2, l_3, θ_1, $\Delta\theta_2$, $\Delta\theta_3$, r_c

Freestream Conditions

Inflow: equilibrium air

Mach number M_∞	8
Altitude h	30 km
Static pressure p_∞	1197 Pa
Static temperature T_∞	227 K
Dynamic pressure q_∞	53.6 kPa
Reynolds number Re_∞	2.26×10^5

Design Objectives

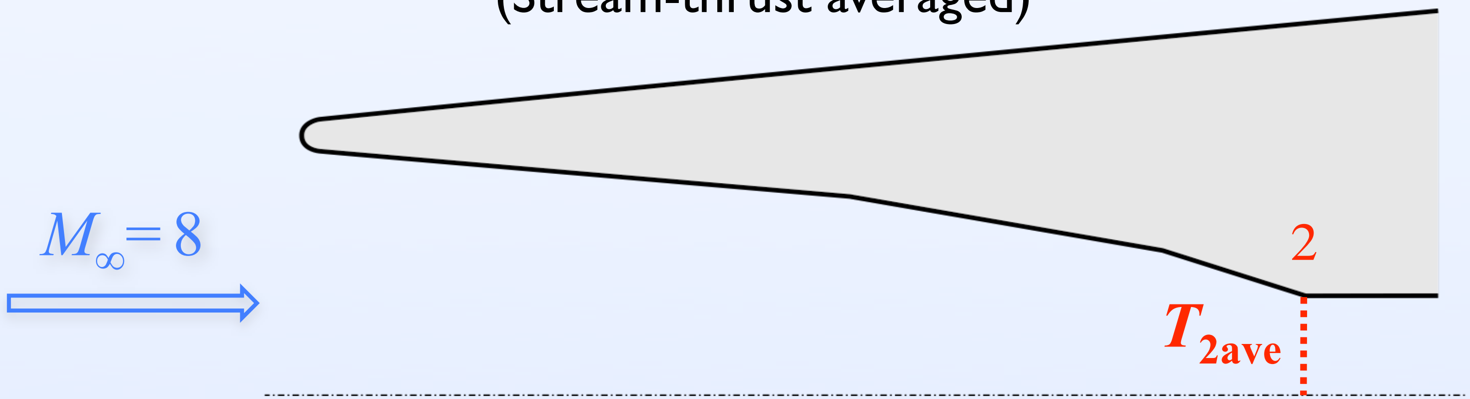
Minimise:

- Inlet drag = $\boldsymbol{D}_{\text{inlet}}$
- Compression efficiency loss = $1-\eta_B$
- Maximum adverse pressure gradient = $\boldsymbol{dp / ds}_{\max}$

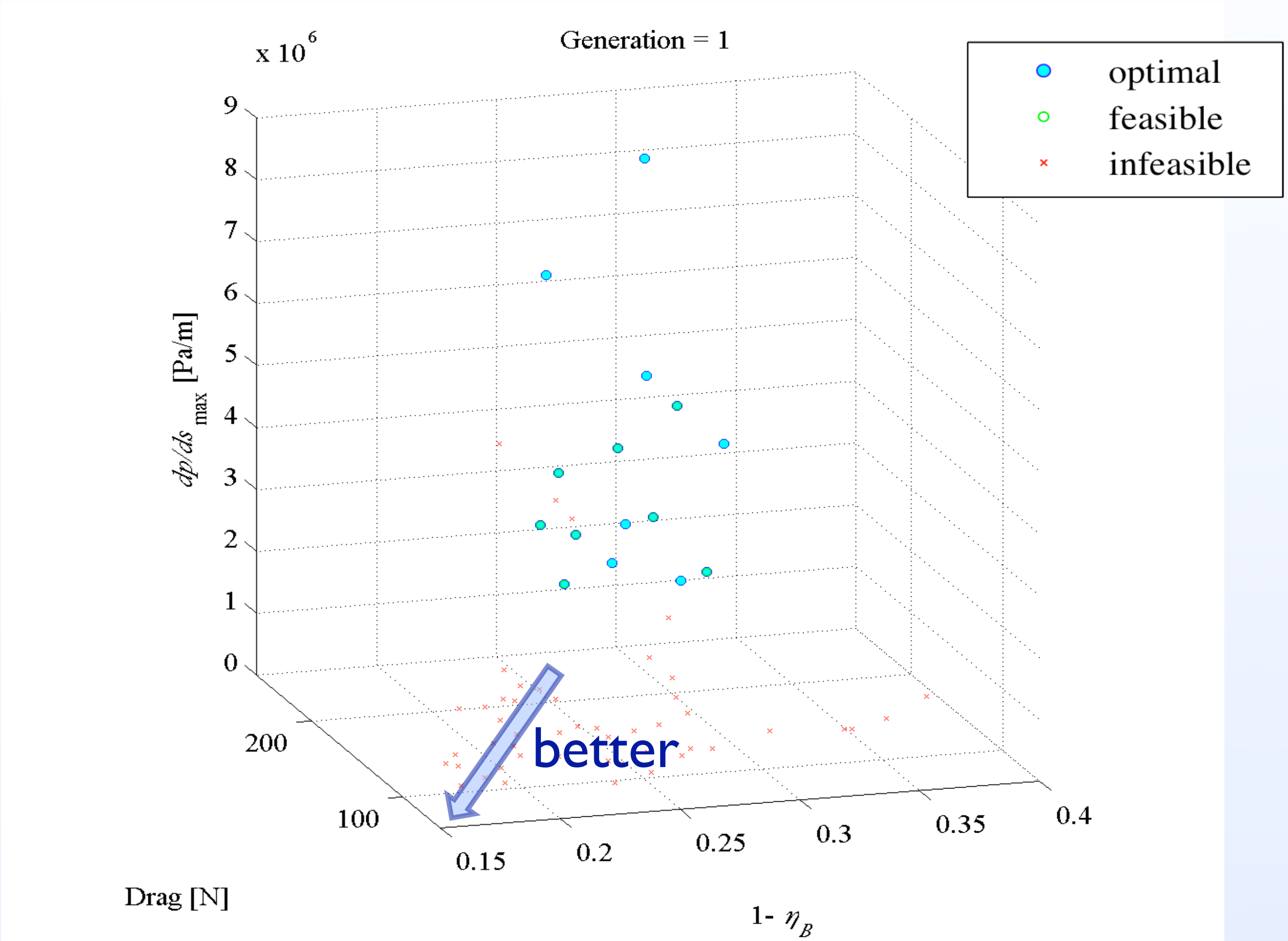
Subject to:

- Exit temperature = $\boldsymbol{T}_{\mathbf{2ave}} \geq 850\text{K}$

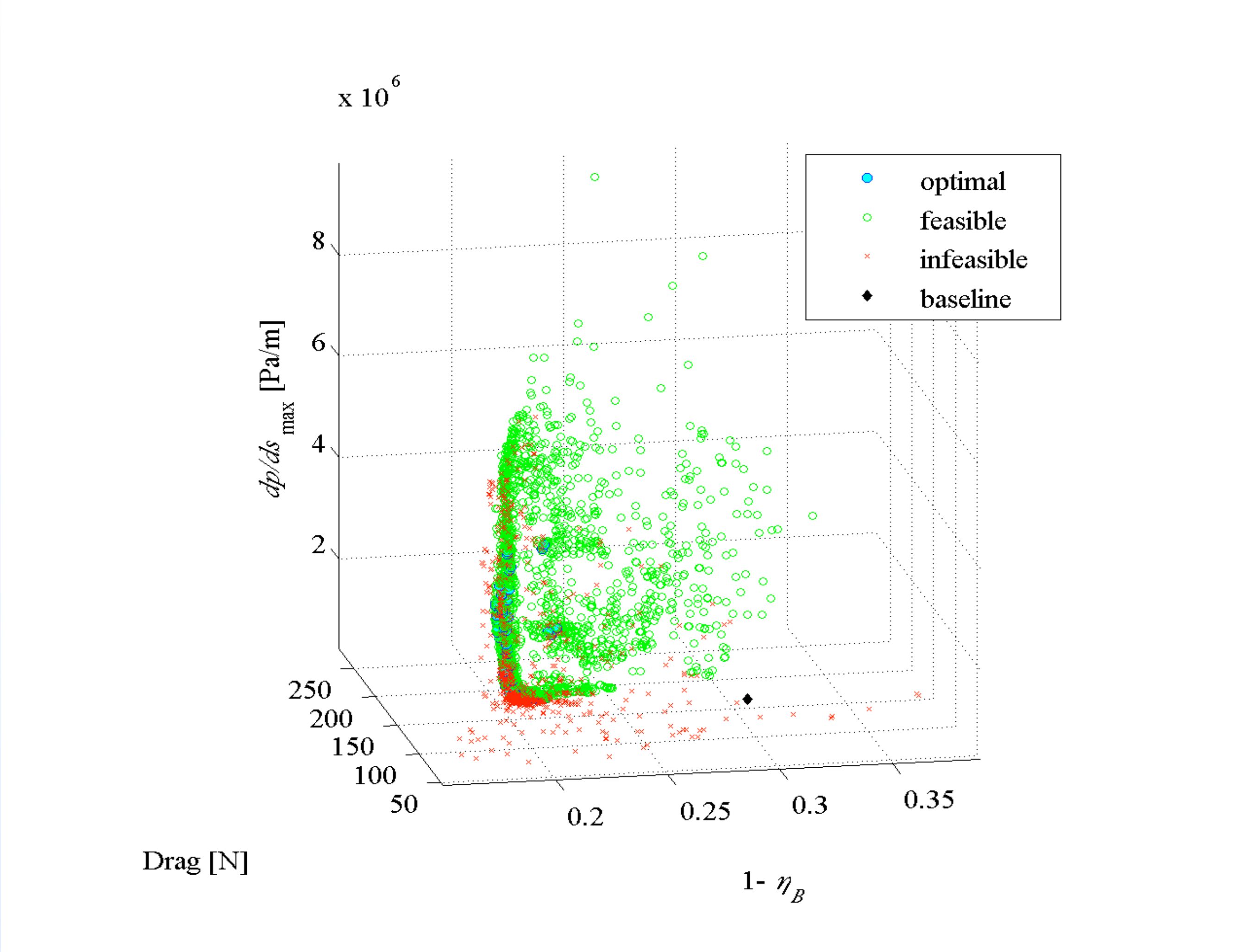
(Stream-thrust averaged)



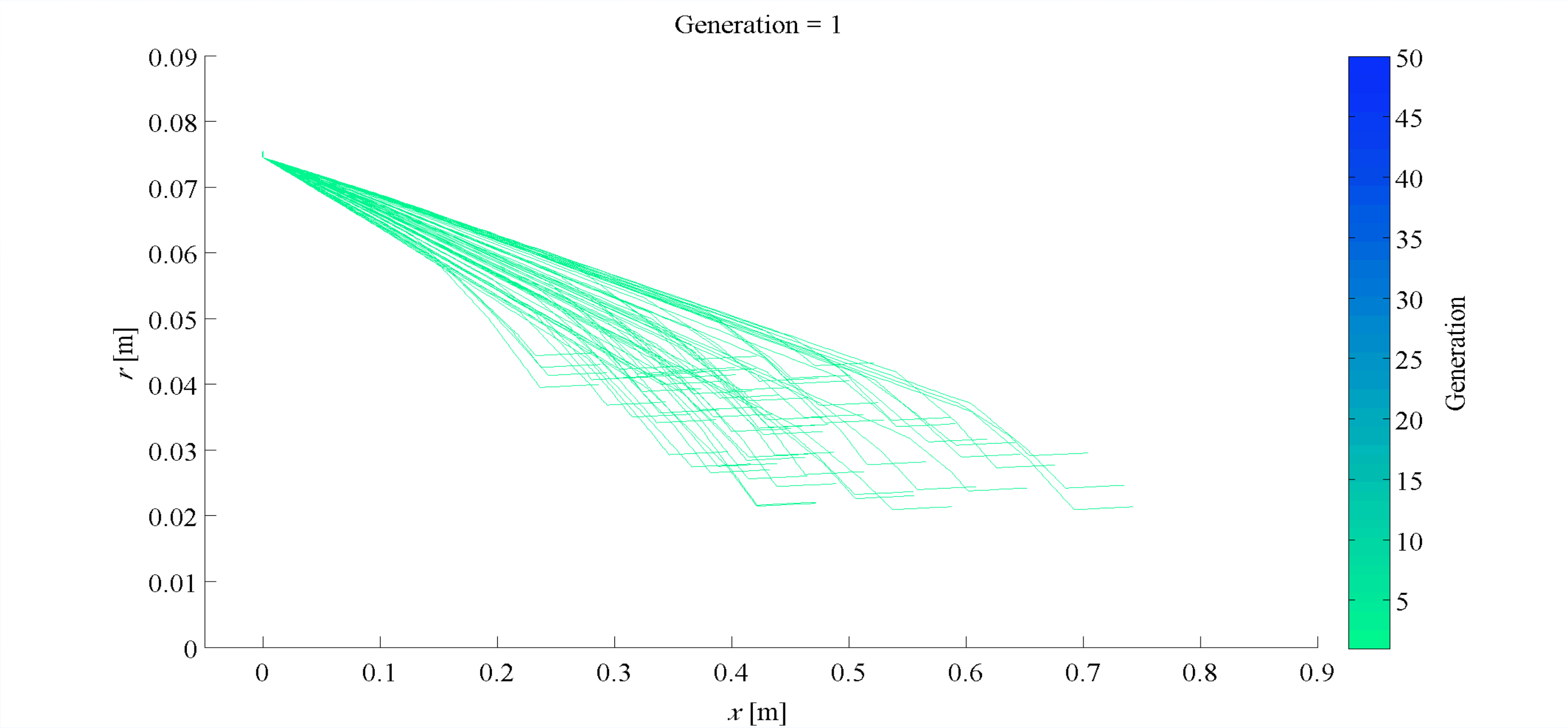
Pareto Optimal Front



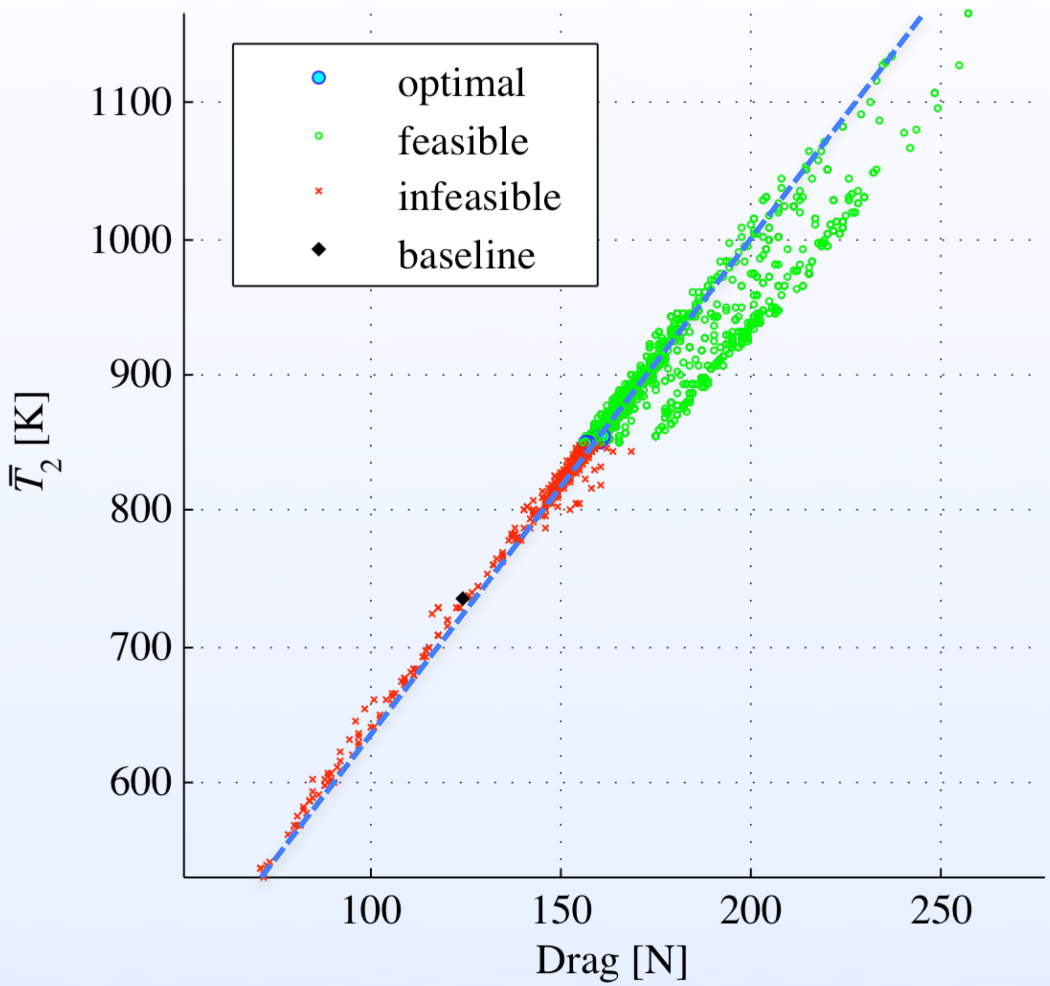
Pareto Optimal Front



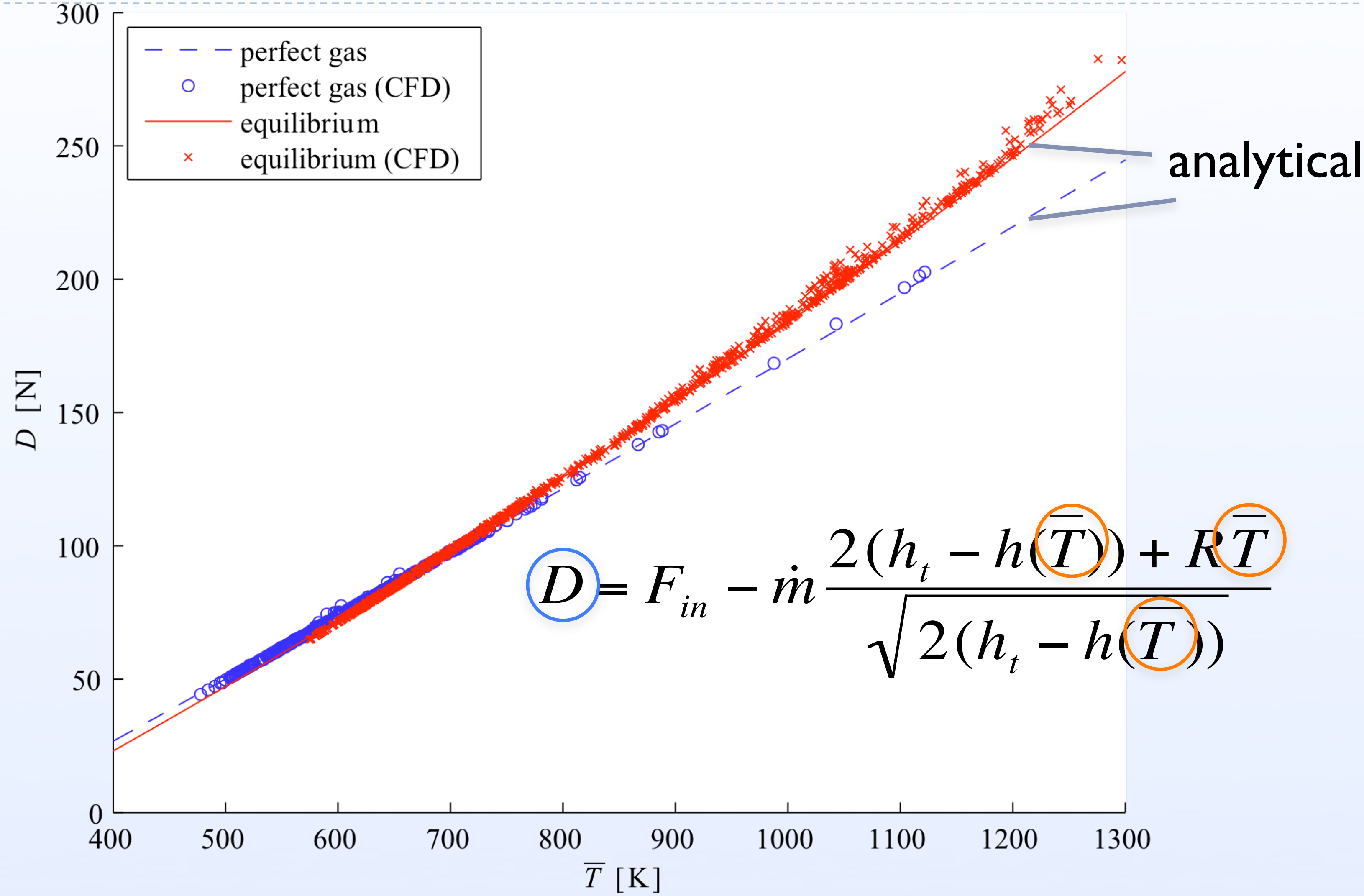
Geometries Evaluated in Optimisation



Inlet Drag and Exit Temperature

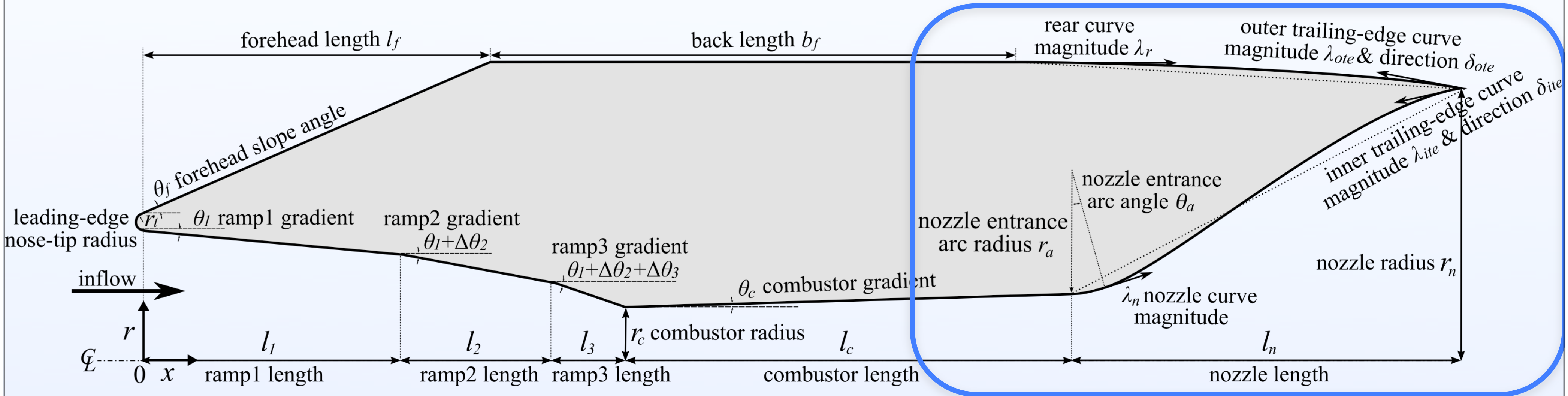


Inlet Drag and Exit Temperature

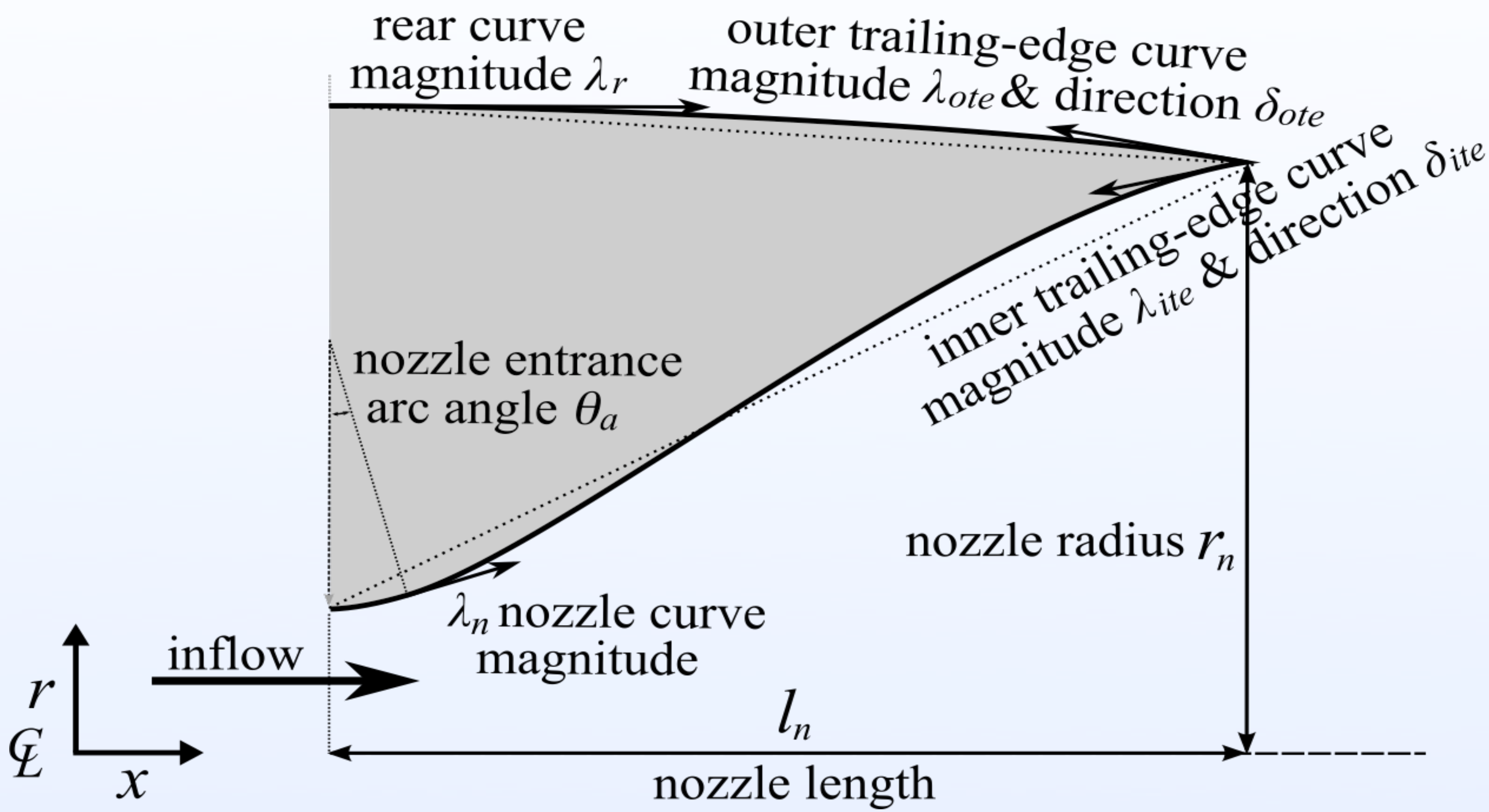


$$D = F_{in} - \dot{m}\frac{2(h_t - h(\overline{T})) + R\overline{T}}{\sqrt{2(h_t - h(\overline{T}))}}$$

Design Parameters

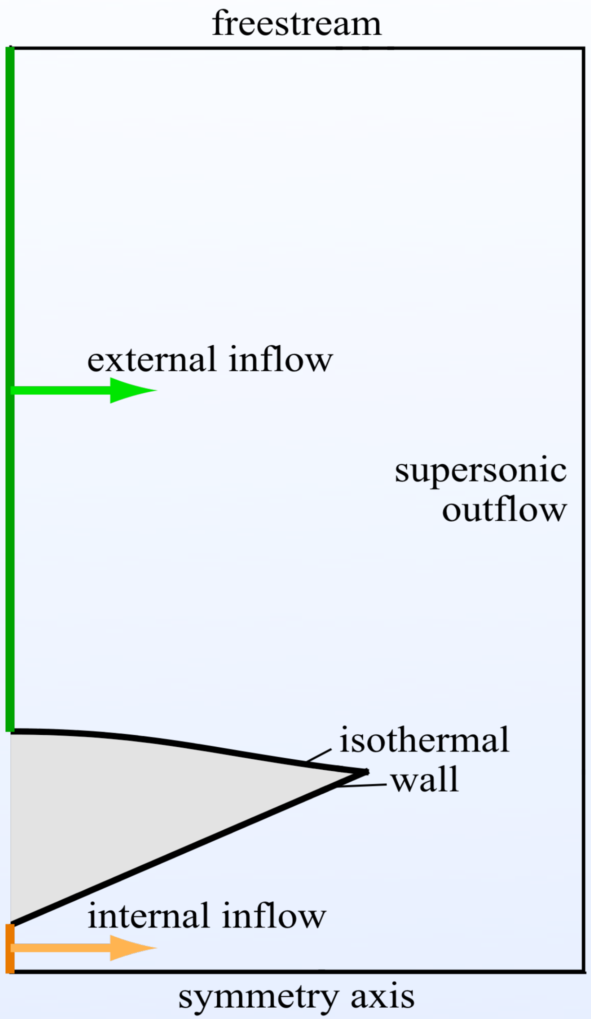


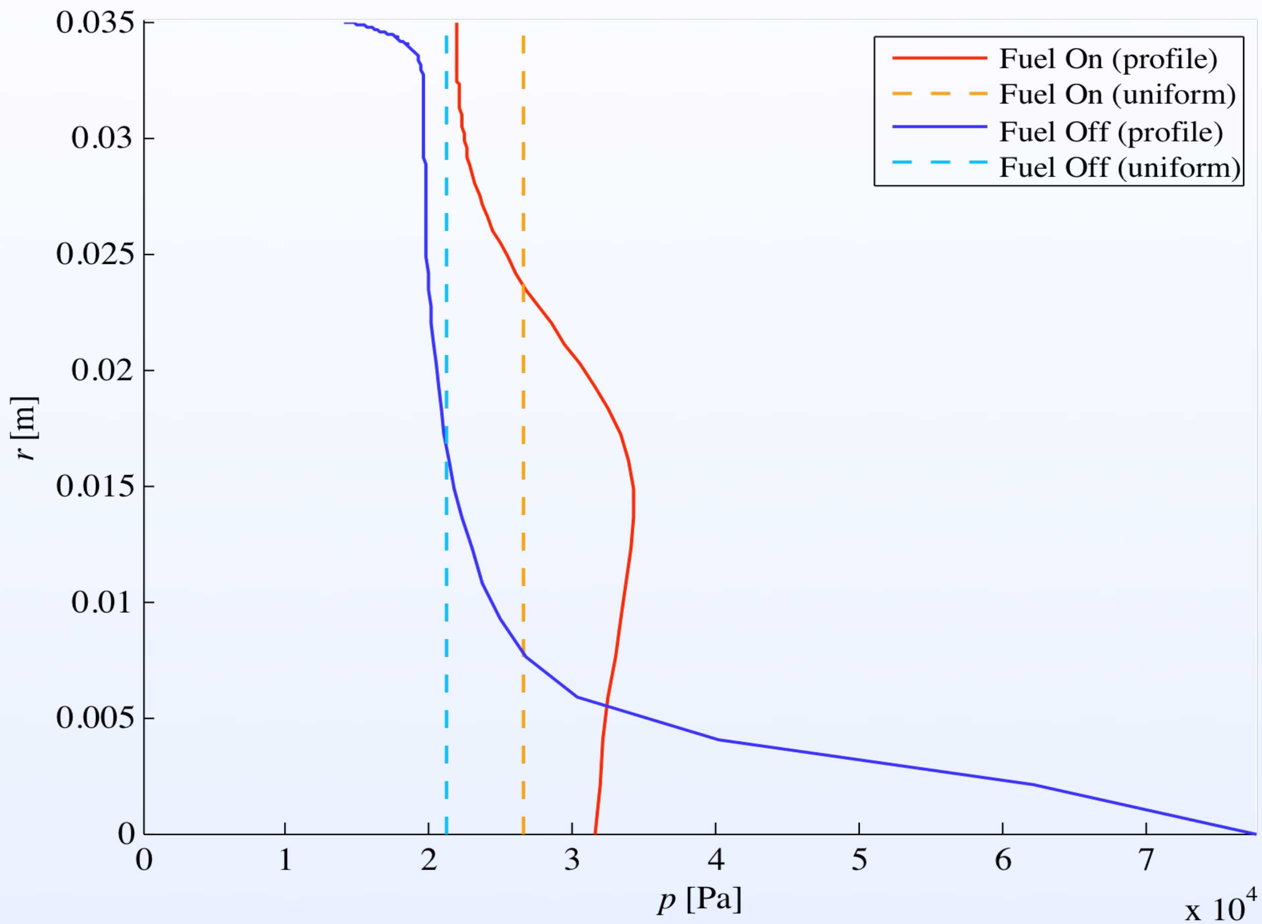
Decision Variables



9 decision variables

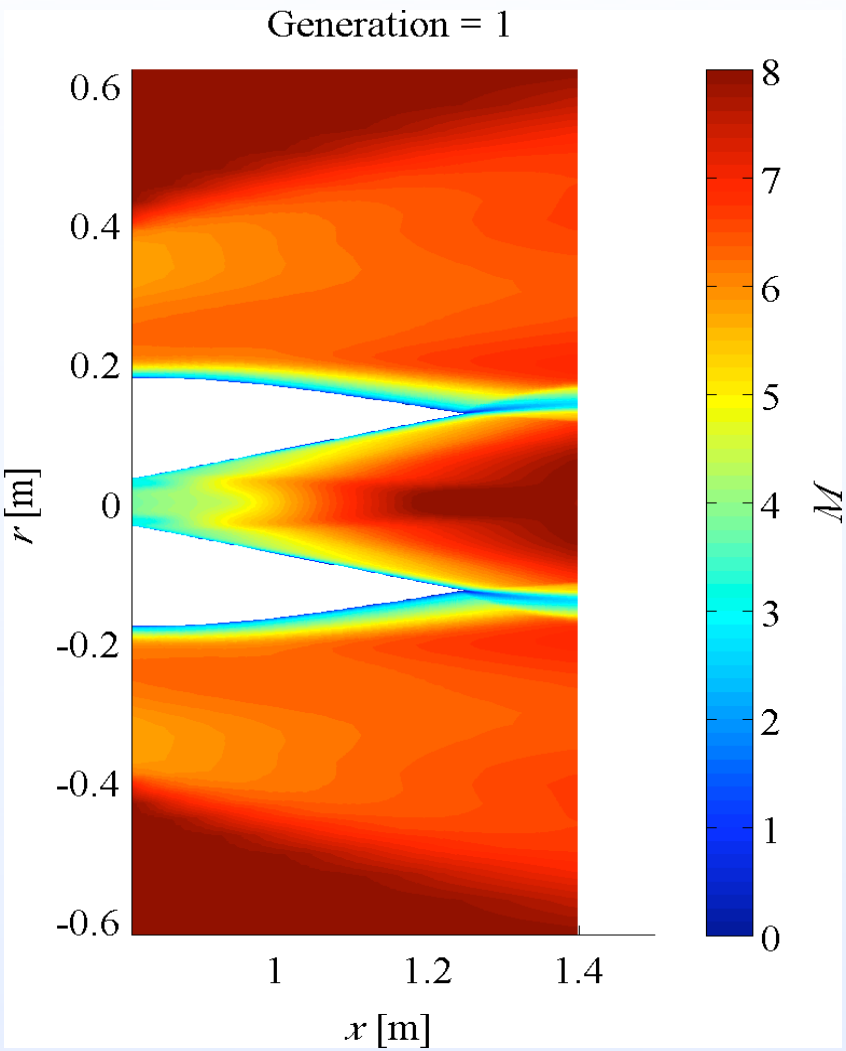
Boundary Conditions



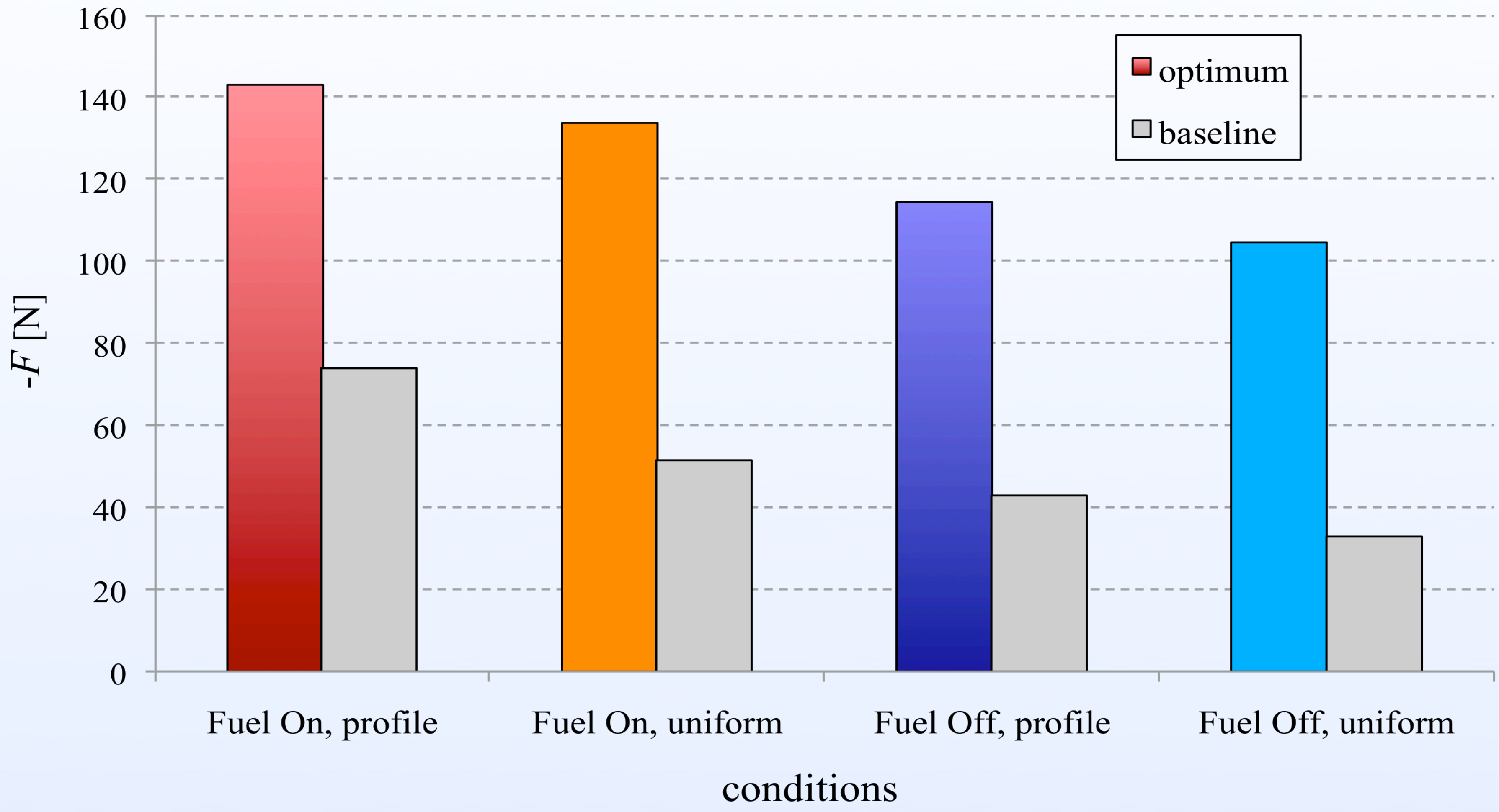


Pressure profiles at nozzle entrance

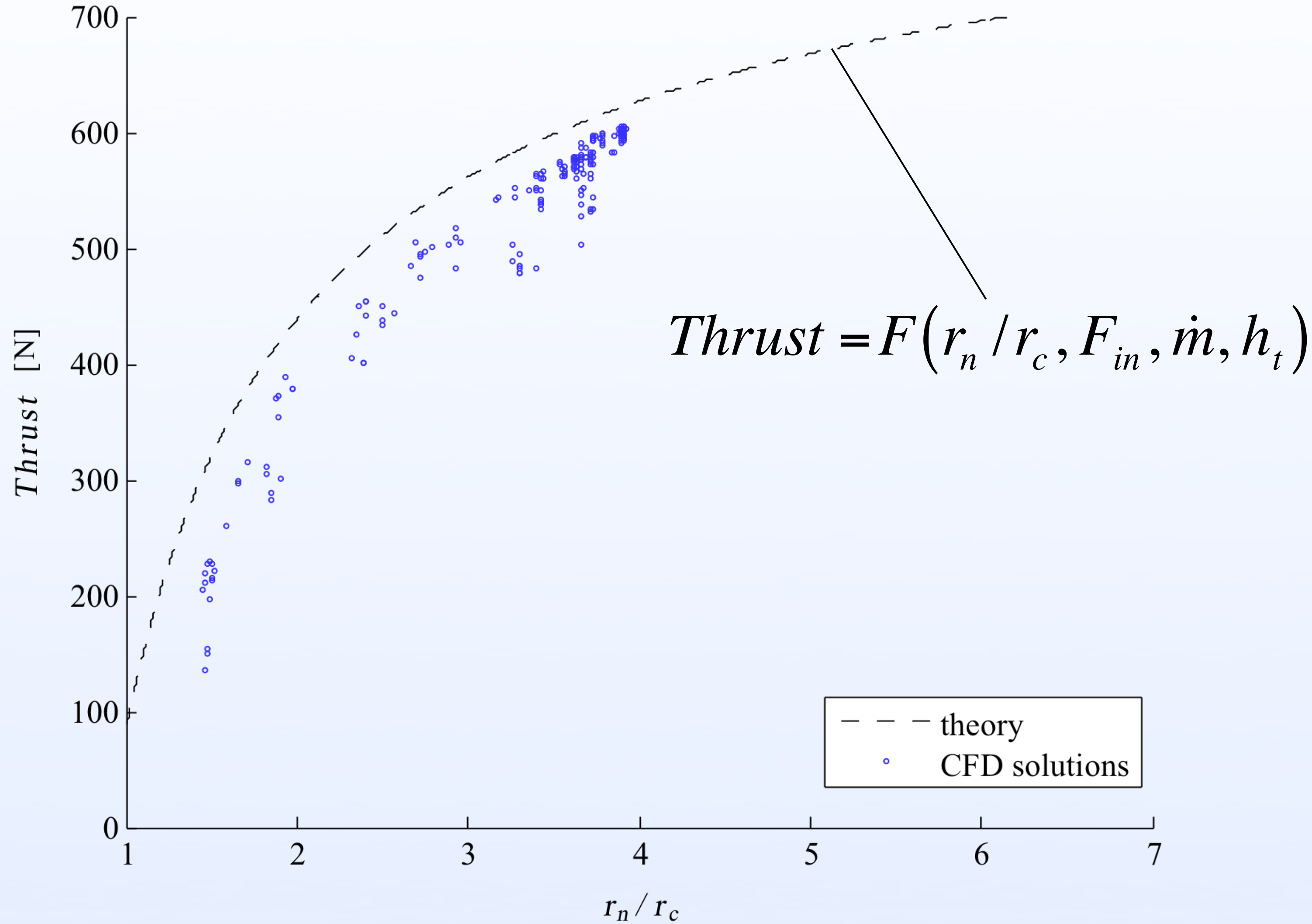
Optimisation Progression



Thrust Comparison

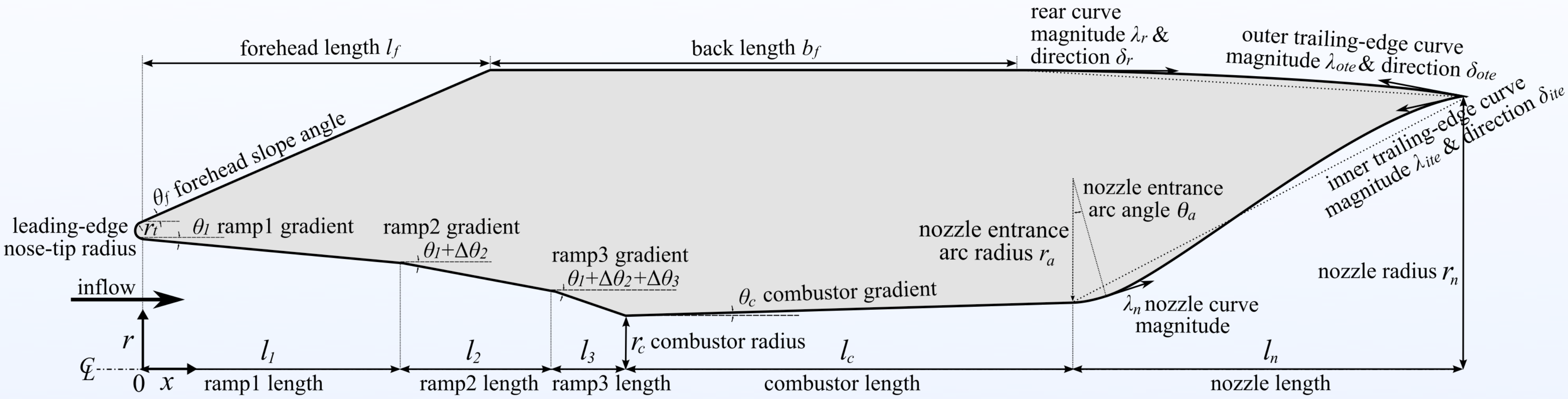


Thrust and Nozzle radius



Full Flow-Path Optimisation

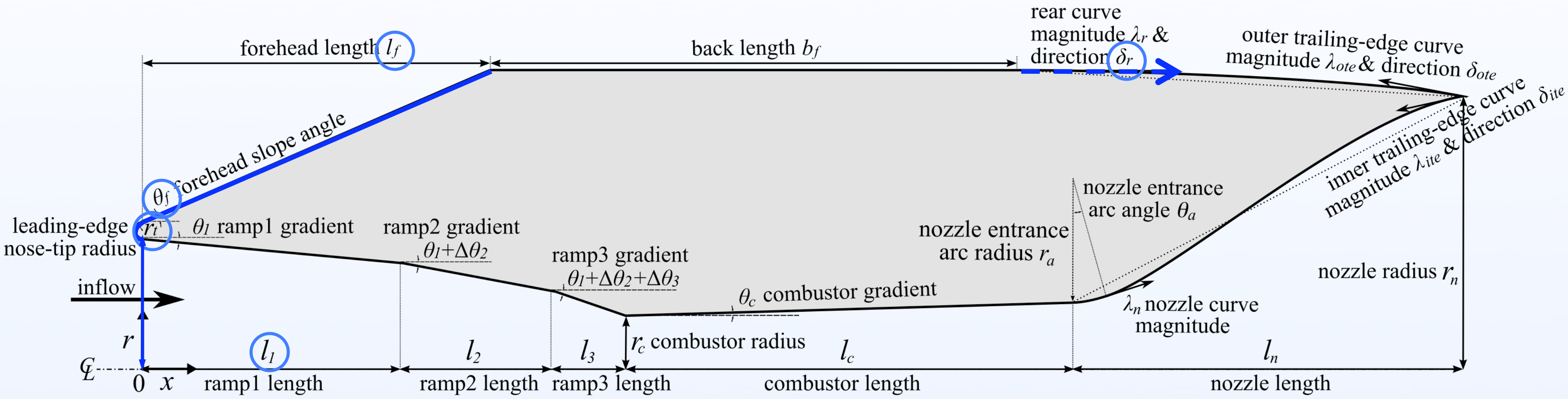
24 design parameters



Geometric representation of axisymmetric scramjet engine

Design Objectives

24 - 5 = 19 decision variables



- Maximise: net thrust (= minimise total drag F_x)
- Subject to: CFD convergence $\geq 10^{-2}$

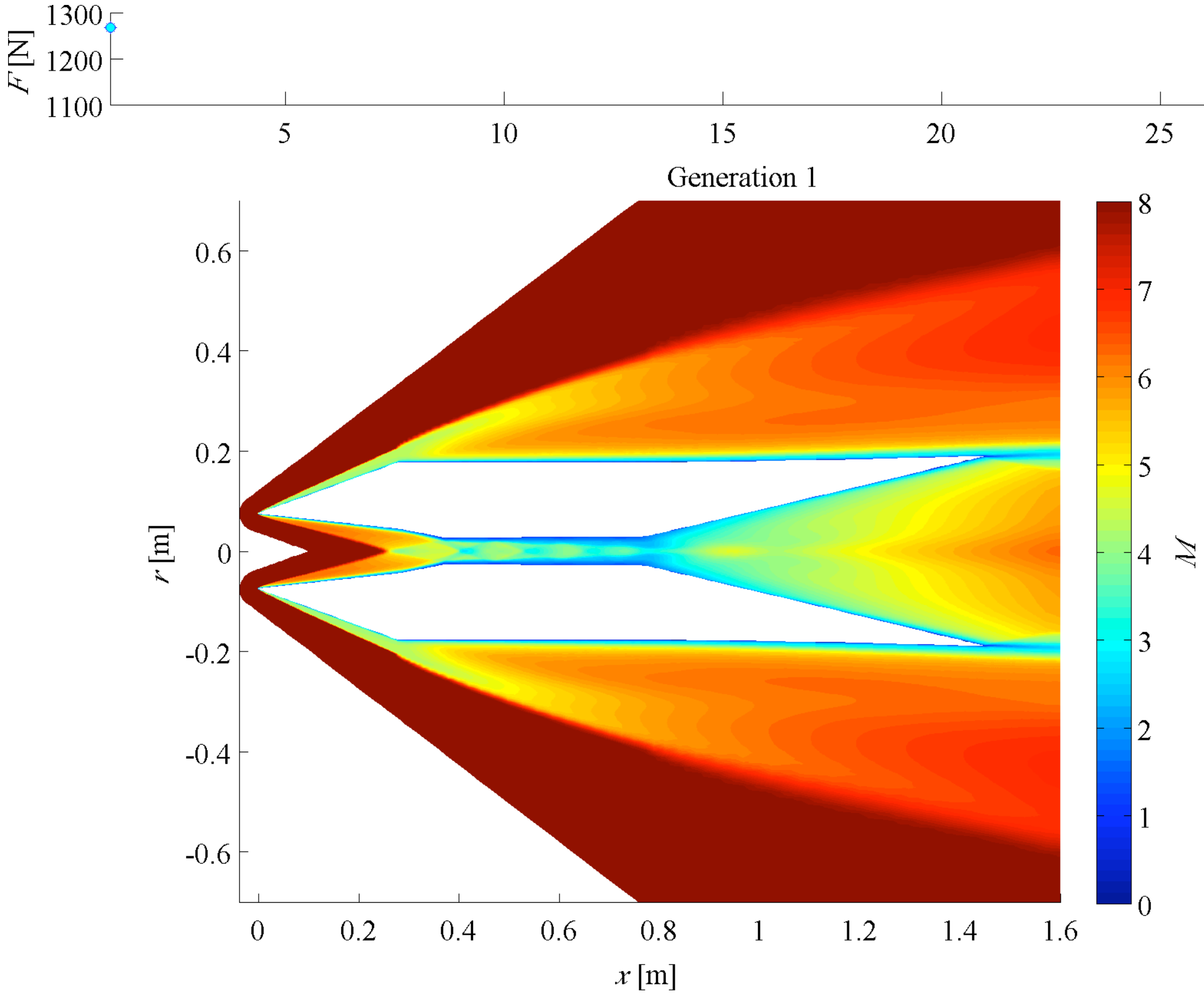
Design variables: $x_{Li} \leq x_i \leq x_{Ui}$ $(i = 1, \ldots, 19)$

Freestream Conditions

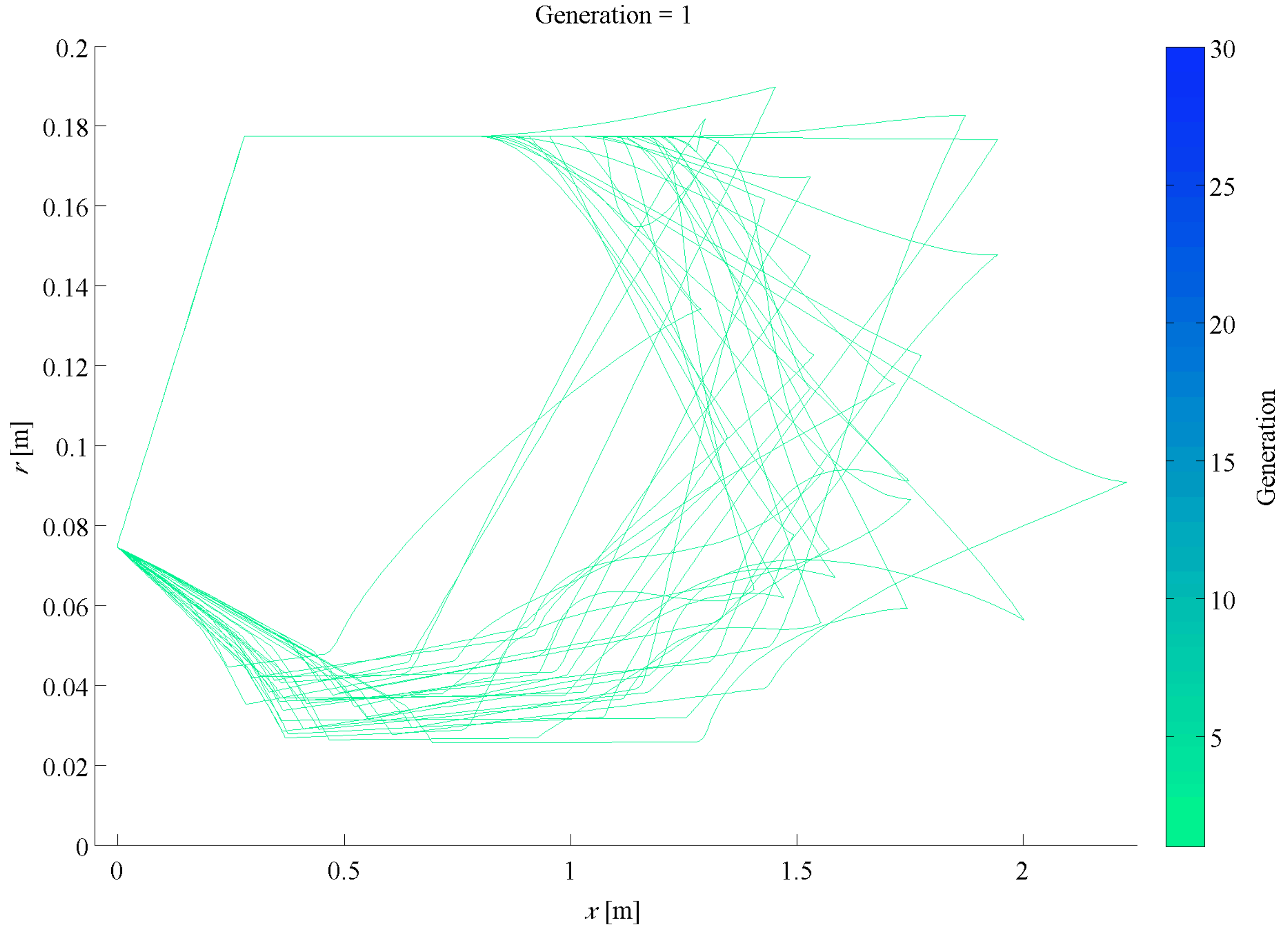
Inflow: premixed fuel (H_2) / air
(equivalence ratio Φ = 80%)

Mach number M_∞	8
Altitude h	30 km
Static pressure p_∞	1197 Pa
Static temperature T_∞	227 K
Dynamic pressure q_∞	53.6 kPa
Reynolds number Re_∞	2.26×10^5

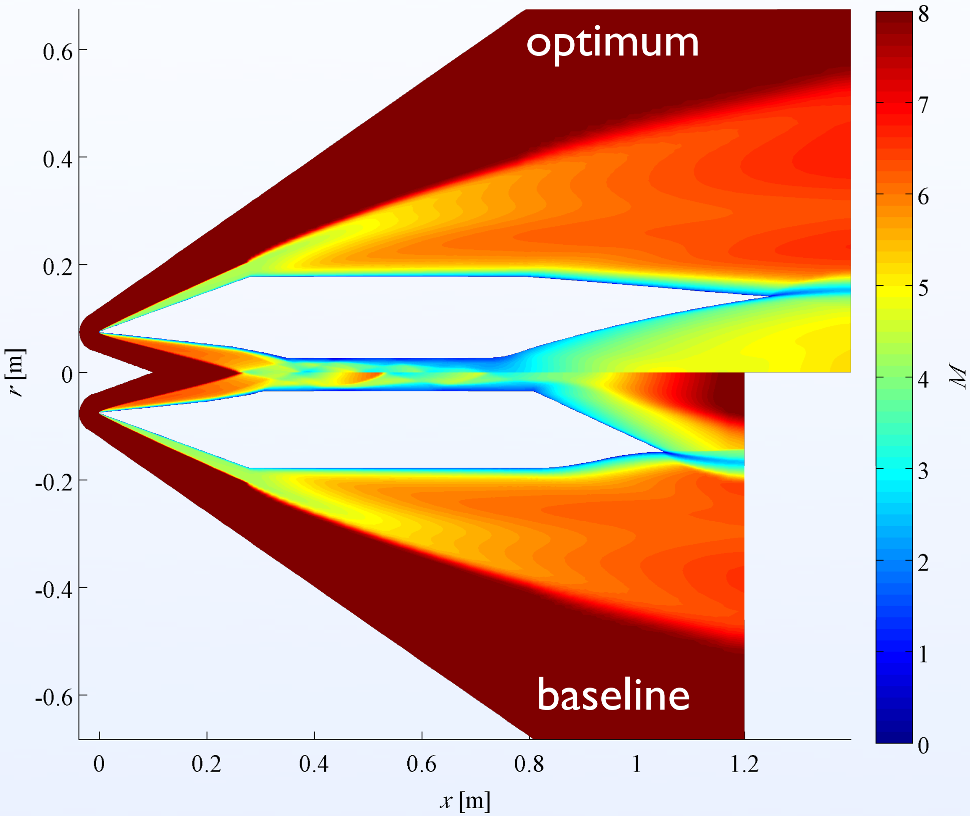
Optimum Geometry Progression



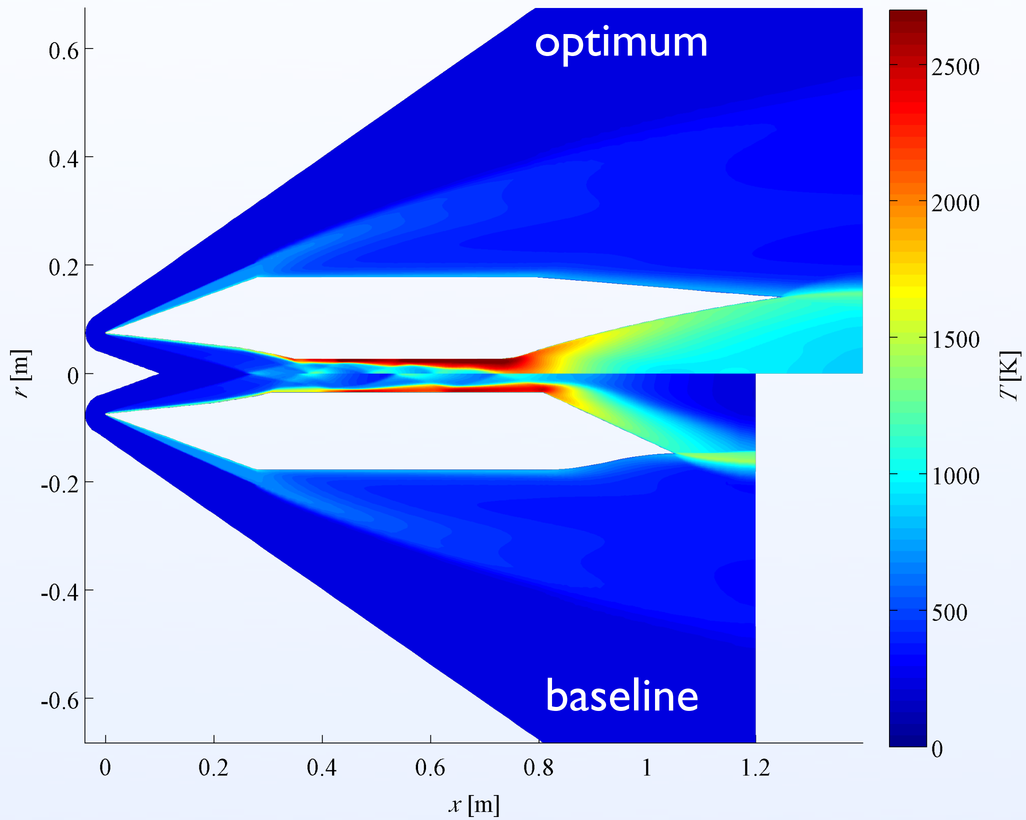
Evaluated Geometries



Flowfield Comparison

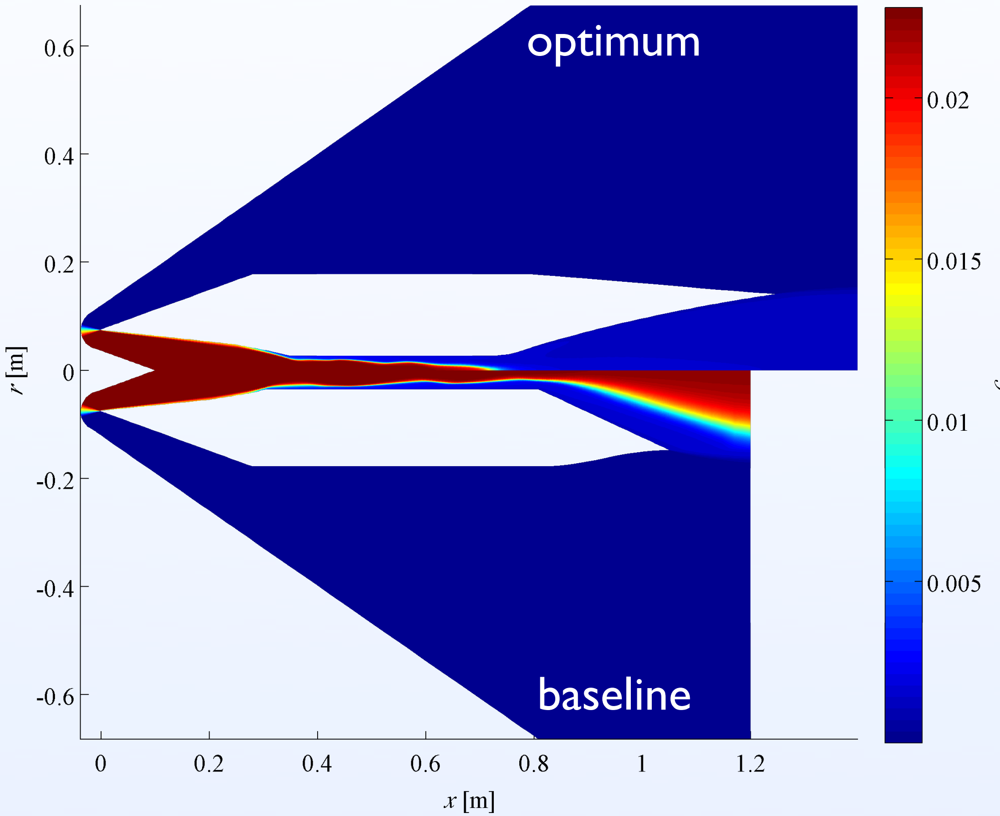


Mach number

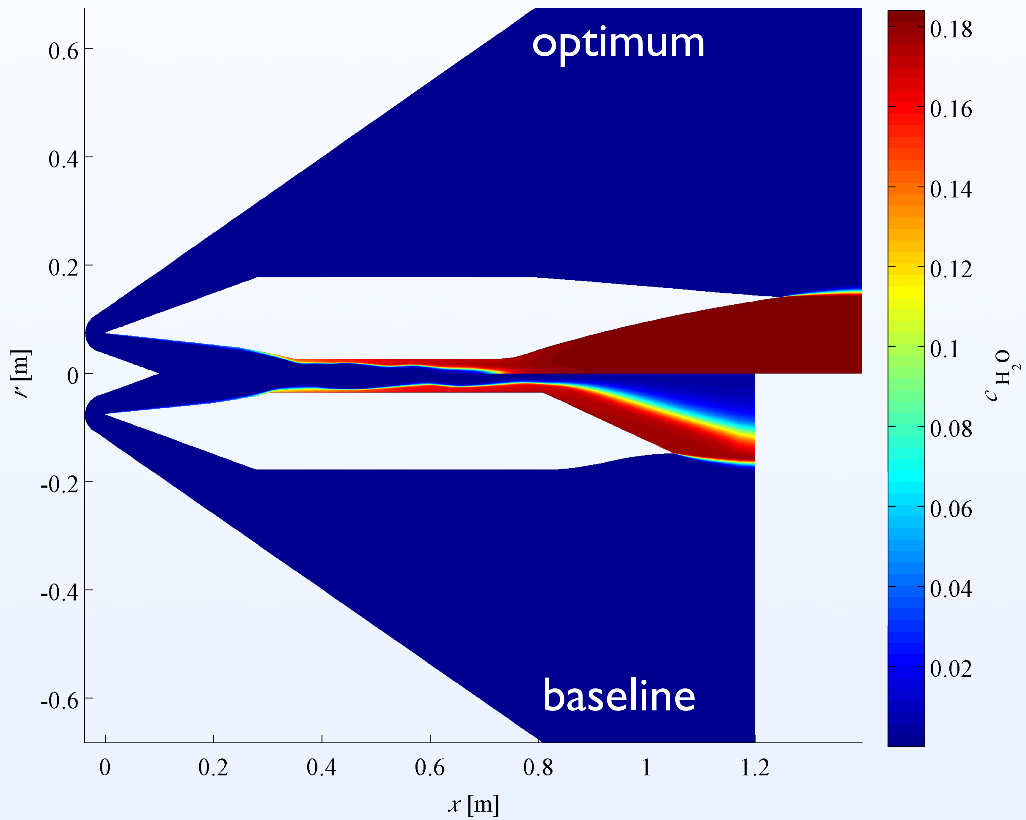


temperature

Flowfield Comparison



H₂ mass fraction

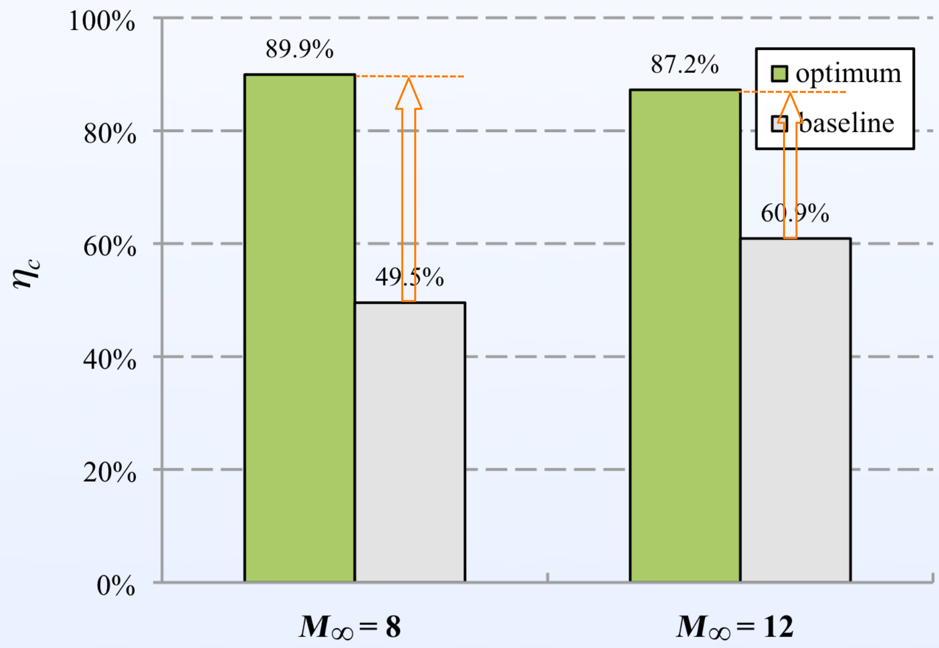


H_2O mass fraction

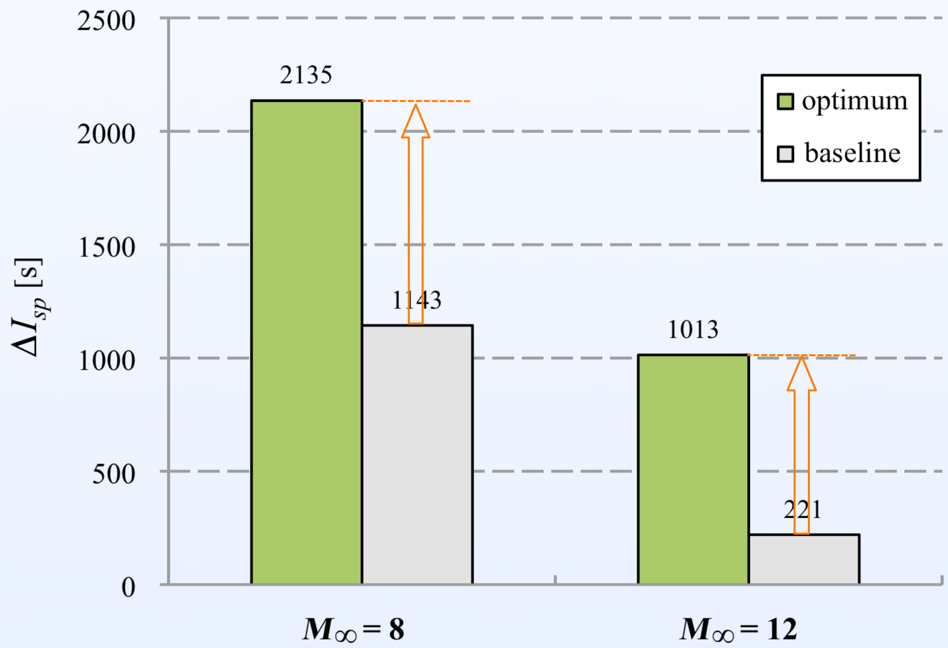
Overall Performance

$$\eta_c \equiv 1 - \frac{\overline{c_{H_2}}}{c_{H_2 i}} = 0.0228 \text{ for premixed fuel / air of } \Phi = 0.8$$

$$\Delta I_{sp} = \frac{\Delta F_x}{\dot{m}_{H_2 i}\, g} \qquad \Delta F_x = F_{x\,(\text{fuel on})} - F_{x\,(\text{fuel off})}$$

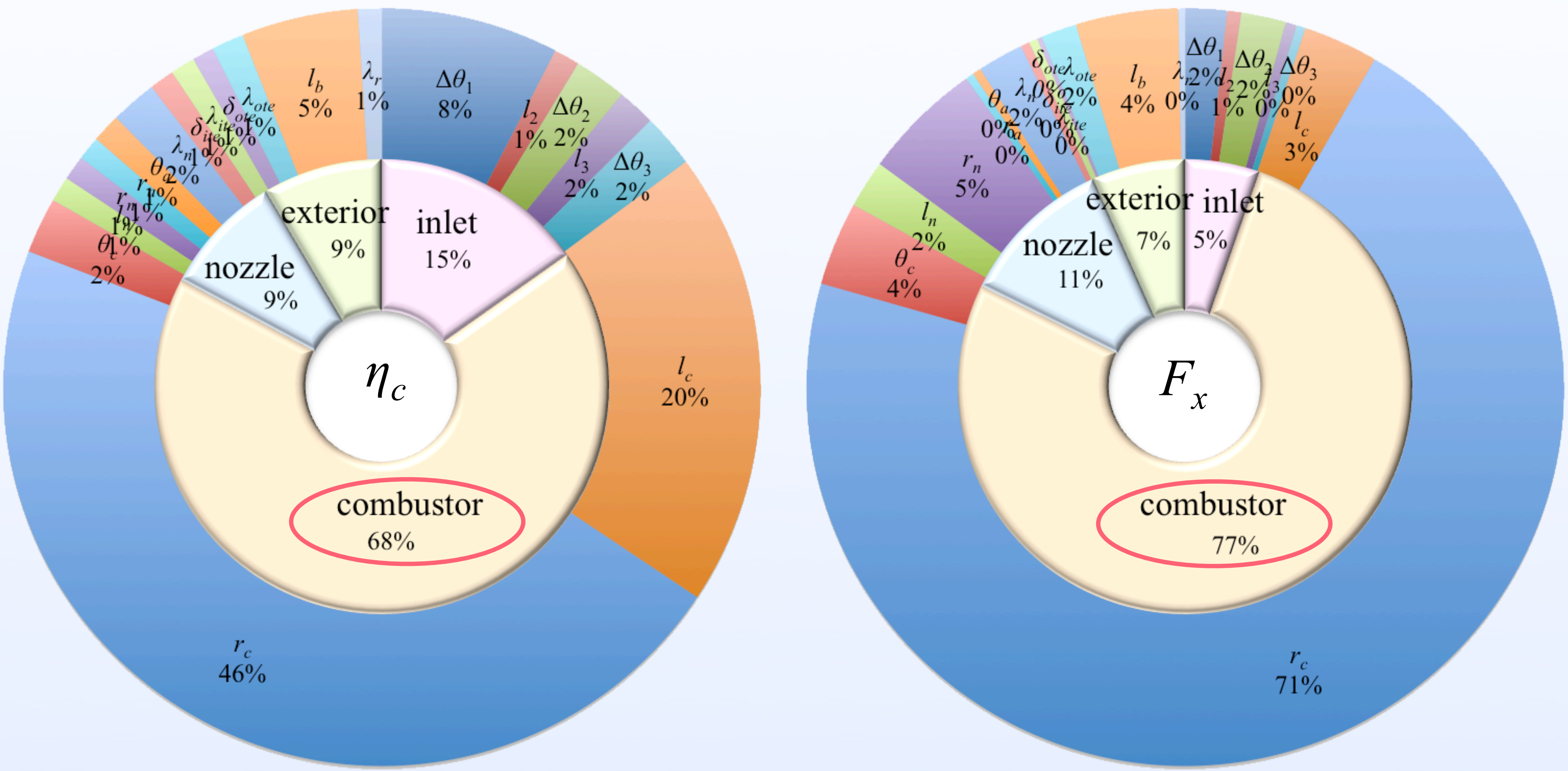


combustion efficiency

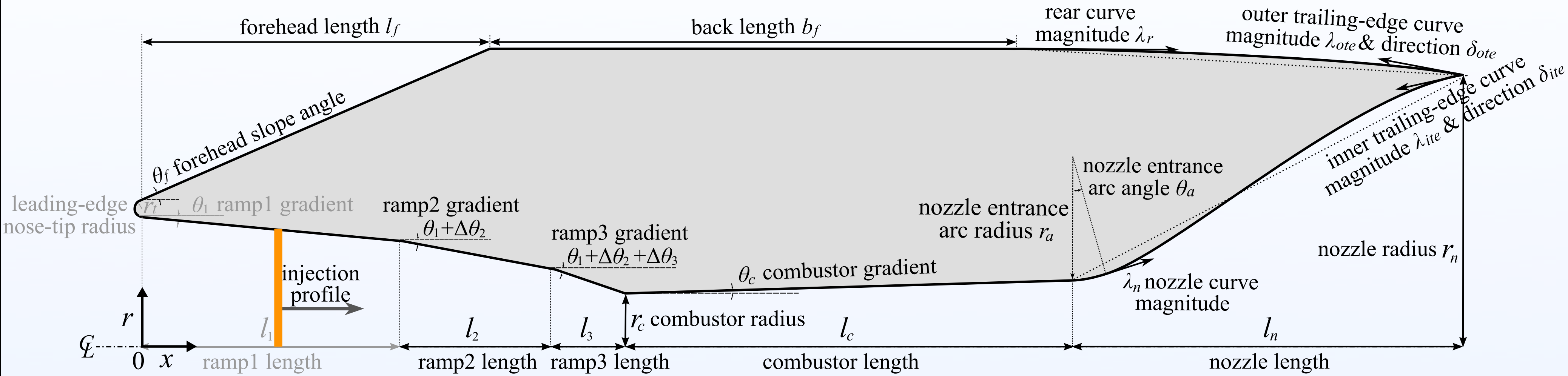


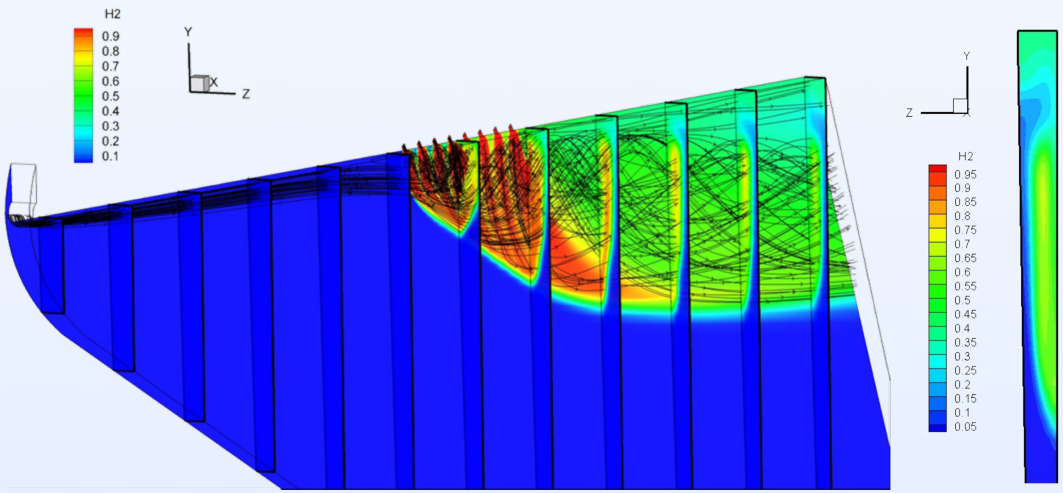
incremental specific impulse

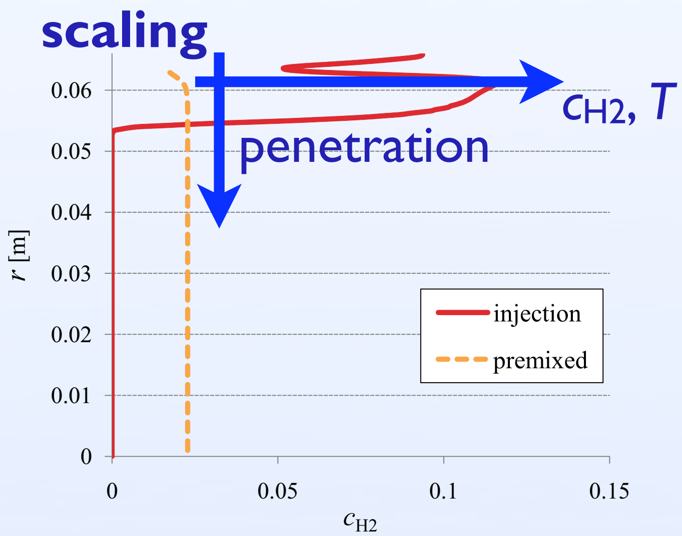
Sensitivity Analysis



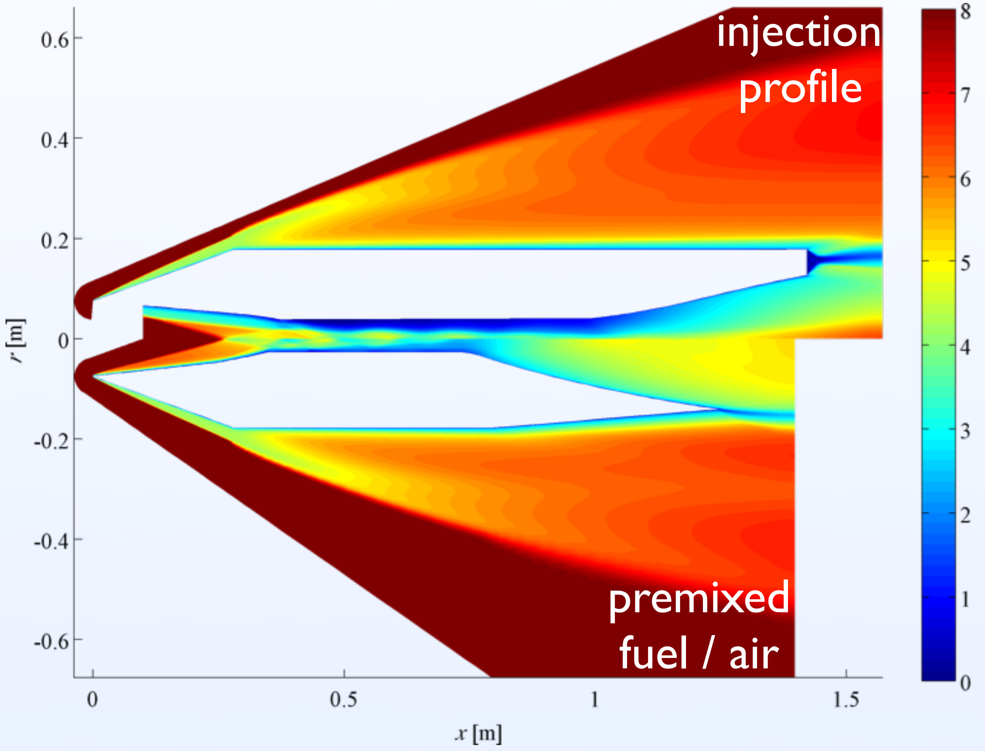
Full Flow-Path Optimisation with Injection Profile



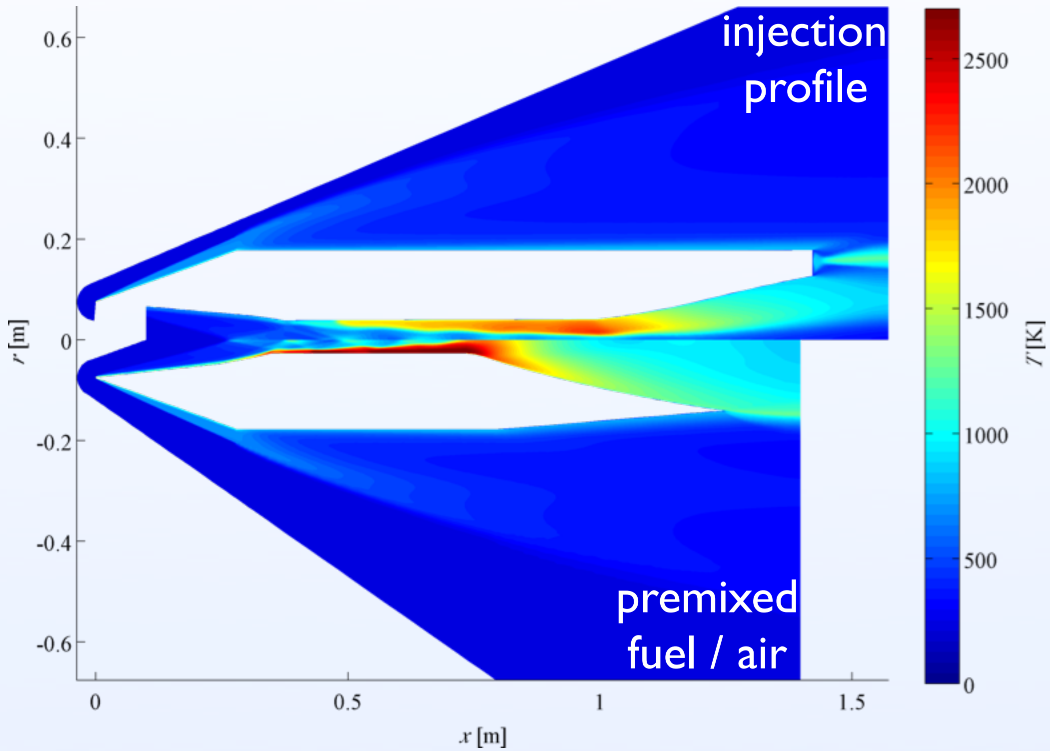




Optimum Flowfield Comparison



Mach number



temperature

Conclusions

- The capability of coupled CFD / MDO approach with surrogate-assisted evolutionary algorithms has been demonstrated in design optimisation problems of axisymmetric scramjets.
- 3-objective optimisation has been performed for the inlet and single objective optimisation (for maximum thrust) has been performed for the nozzle and full flow-path configuration.
- The performance has been improved considerably as a result of optimisation and flowfield analysis has led to significant physical insight including correlations for the inlet drag and nozzle thrust.
- New optimisation capabilities to be employed in forthcoming studies:
  - Surrogate-assisted robust design optimisation
  - Infeasiblility-driven evolutionary algorithms (IDEA)
  - Hybrid design space search (global + local search)